METHOD AND APPARATUS FOR THREE-DIMENSIONAL VIDEO-OCULOGRAPHY

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Patent Application No. 60/541,590, filed February 4, 2004, by the present inventors and assigned to The Johns Hopkins University.

STATEMENT AS TO FEDERALLY SPONSORED RESEARCH

1   BACKGROUND OF THE INVENTION

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3   1.   FIELD OF THE INVENTION

4   This invention relates to oculography (i.e., eye movement recordings) and

5   methods and devices for making non-contact measurements of the rotations of

6   essentially spherical bodies. More particularly, the present invention relates to

7   inexpensive, real-time, three-dimensional, video-oculography that utilizes a

8   specialized marker array which is placed on the eye.

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13   2.   DESCRIPTION OF PRIOR ART

14   Precise and accurate measurement of eye rotation is essential for the

15   clinical evaluation and scientific study of vestibular (balance) and oculomotor

16   (eye movement) disorders. Common types of such disorders often result in those

17   afflicted reporting problems with dizziness.

18   The magnitude of such disorders can be noted by observing that over

19   ninety million Americans suffer from dizziness; it is the ninth most common

20   reason adults visit a primary care doctor. Thirty-four percent of Americans age

21   65-74 suffer from dizziness significant enough to limit their activities of daily life,

22   making it the third most common medical complaint among this group; dizziness

23   is the most common complaint in patients 75 years and older.

24   Eye rotation measurements are also important because they can be used in

25   other applications, such as input to various computer systems for assorted

26   purposes: data entry, command and control (e.g., navigation of computer-

27   controlled equipment), communication, and the enhancement of virtual reality-

28   based displays.

29   The "gold standard" method for measuring three-dimensional eye position

30   is the scleral search coil technique. It involves search coils being either implanted

31   on or affixed to the eye and their orientation identified by subjecting them to

32   uniform, stable magnetic fields. However, even this method can suffer from a

33   number of drawbacks that can affect measurement reliability (e.g., implantation of

34   search coils can restrict or distort eye movements due to eye scarring and

1   inflammation or coil lead tension, the imposed magnetic field can be distorted by

2   metallic objects and by currents flowing in nearby equipment).

3   These drawbacks of the search coil technique have prompted efforts to

4   develop video-oculographic (VOG) systems for the measurement of three-

5   dimensional eye rotations. See FIG. 1 for a description of the coordinate system

6   and the terminology used herein to describe rotational eye movements.

7   These systems typically make two-dimensional (horizontal and vertical)

8   eye rotation determinations by tracking the pupil and/or a corneal reflection.

9   To determine eye rotations in a third dimension (torsional), most currently

10   available VOG systems either track two or more landmarks on the eye or measure

11   and track changes in iral contrast along a circular sampling path. In humans,

12   pronounced iral striations make iral contrast tracking practical, whereas, in

13   animals that do not have pronounced iral striations, it is more practical to track

14   attached landmarks.

15   However, there are problems with these methodologies and the

16   conventional VOG systems. For example, the quality of data using existing

17   methods is often compromised due to misalignment of the camera with the eye.

18   This misalignment can introduce errors > 10%. Reflections of the light source on

19   the eye and/or shading of the landmarks/pupil can produce either loss of the

20   landmark or incorrect calculation of its centroid position. VOG techniques that

21   track the pupil are inherently problematic because the contrast between the iris

22   and pupil is not large. This non-exact demarcation zone makes it difficult to

23   precisely define the pupil region and calculate the pupil centroid position.

24   Additionally, current three-degree eye measurement VOG systems that

25   track landmarks on the eye employ complex and relatively inefficient algorithms.

26   Most require considerable post-hoc processing of the data collected to enable

27   computation of an eye's torsional movements. Meanwhile, those few systems that

28   provide real-time measurements of eye torsional motions are prohibitively

29   expensive for most clinical and diagnostic applications. Most of these commercial

30   systems are for human applications only i.e. they track the pupil and iral signature.

31   Given the same technological limitations pupil/iral tracking is significantly slower

32   than landmark tracking.

33   Current methods and devices for measuring three-dimensional eye

34   movements need to be improved by making them: (a) less expensive, (b) more

35   portable so that such measurements can be made other than in only clinical

laboratory settings, and (c) faster operating so to enable them to provide real-time measurements which can be more timely correlated for diagnostic purposes with the bodily motions which may be precipitating such eye movements.

The present inventors have been working in this technical field and towards the development of such improved methods and devices for some time. Much of their earlier research is applicable to the methodologies described herein and has been documented in the scientific literature. See for example: Migliaccio, MacDougall, Minor and Della Santina, "Inexpensive System for Real-Time 3-Dimensional Video-Oculography Using a Fluorescent Marker Array," submitted for publication to the Journal of Neuroscience Methods, February 2004, and MacDougall, "The Human Eye-Movement Response To Maintained Surface Galvanic Vestibular Stimulation," Ph.D. dissertation, University of Sydney, May 2003.

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4   3.   OBJECTS AND ADVANTAGES

5   There has been summarized above, rather broadly, the background that is

6   related to the present invention in order that the context of the present invention

7   may be better understood and appreciated. In this regard, it is instructive to also

8   consider the objects and advantages of the present invention.

9   It is an object of the present invention to provide improved, lower cost

10   methods and devices for making eye rotation measurements.

11   It is another object of the present invention to provide improved, more

12   portable methods and devices for making eye rotation measurements.

13   It is yet another object of the present invention to provide improved, faster

14   operating methods and devices for making eye rotation measurements.

15   It is a further object of the present invention to provide improved

16   diagnostic methods and devices for assessing vestibular and oculomotor disorders.

17   It is also an object of the present invention to provide improved methods

18   and devices for providing eye rotation measurement input to various computer

19   systems for a wide assortment of applications (e.g., data entry, command and

20   control, communication, and the enhancement of virtual reality-based displays).

21   These and other objects and advantages of the present invention will

22   become readily apparent as the invention is better understood by reference to the

23   accompanying summary, drawings and the detailed description that follows.

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3   SUMMARY OF THE INVENTION

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5   Recognizing the needs for the development of improved methods and

6   apparatuses for making eye rotation measurements, the present invention is

7   generally directed to satisfying the needs set forth above and overcoming the

8   disadvantages identified with prior art devices and methods.

9   In a first preferred embodiment, such a method for measuring the three-

10   dimensional movements of an eye includes the steps of: (a) marking an array of

11   positions on the eye whose movements are to be measured, (b) illuminating this

12   marker array with a light source whose output is in a prescribed first spectral

13   range, (c) capturing along a prescribed optical axis the two-dimensional, digital

14   images of this array of eye-marked positions as the eye is moved, wherein these

15   images are captured in a second spectral range that does or does not overlap with

16   the illumination's prescribed first spectral range, (c) wherein this prescribed

17   optical axis having been aligned with the center of the eye, and (d) computing the

18   three-dimensional positions of the array of eye-marked positions from the

19   information contained in the captured digital images.

20   In a still further preferred embodiment, the present invention takes the

21   form of a device for measuring the three-dimensional movements of an eye. This

22   devices includes: (a) a marker array that identifies prescribed positions on the eye

23   whose movements are to be measured, (b) a digital video camera for capturing the

24   two-dimensional, digital images of this marker array as the eye is moved, (c) a

25   light source that illuminates the marker array with an output that is outside the

26   spectral range of the camera, (d) light sources that are used to align the camera's

27   optical axis with the center of the eye, (e) an algorithm for computing the three-

28   dimensional positions of the marker array from the information contained in the

29   captured digital images, and (f) a base for fixing the position of the camera

30   relative to the position of the eye, wherein the materials of the marker array are

31   chosen so that the array has the ability to, when illuminated as described above,

32   give off energy that is in the spectral range of the device's camera.

33   Thus, there has been summarized above, rather broadly, the present

34   invention in order that the detailed description that follows may be better

35   understood and appreciated. There are, of course, additional features of the

1   invention that will be described hereinafter and which will form the subject matter

2   of any eventual claims to this invention.

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1   BRIEF DESCRIPTION OF THE DRAWINGS

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3   FIG. 1 displays the coordinate system and illustrates the terminology used

4   herein to describe rotational eye movements.

5   FIGS. 2a and 2b are schematic top and front views of an experimental set-

6   up of a preferred embodiment of the present invention that has been configured to

7   allow for the eye rotation measurements of a laboratory animal.

8   FIGS. 3a and 3b are schematic side and top views of an experimental set-

9   up of the present invention that has been configured to allow for eye position

10   measurements in humans.

11   FIG. 4 is a schematic of another embodiment of the present invention that

12   is suitable for measuring human eye movements in those instances in which it is

13   desired to not obstruct the patient's view.

14   FIG. 5 illustrates a marker array of the present invention in which the array

15   is place on an annular contact lens which is to be worn by the patient whose eye

16   movements are to be measured.

17   FIGS. 6a-6b illustrate the eye rotational position calculation aspects of the

18   present invention.

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Before explaining at least one embodiment of the present invention in detail, it is to be understood that the invention is not limited in its application to the details of construction and to the arrangements of the components set forth in the following description or illustrated in the drawings. The invention is capable of other embodiments and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting.

Although the foregoing disclosure relates to preferred embodiments of the invention, it is understood that these details have been given for the purposes of clarification only. Various changes and modifications of the invention will be apparent, to one having ordinary skill in the art, without departing from the spirit and scope of the invention.

Described herein is an inexpensive technique and device **1** for the real-time measurement of three-dimensional eye position. In a preferred embodiment, it uses a digital video camera **2** with a modified lens **4** to track an array of three 1mm x 1 mm markers **6** on a piece of plastic film **8** that is affixed to the cornea or sclera of the eye. Depending on the spectral sensitivity of the specific camera **2** used, an optical filter or filtering mirror **10** can be used to improve the contrast observed by the camera.

To increase contrast between the markers **6** and unwanted corneal reflections, the markers **6**, in a first preferred embodiment, can be fabricated from materials that give them a fluorescent property. The markers are illuminated with an ultra-violet light source **12** whose output is outside the camera's range of spectral sensitivity.

The experimental arrangement and alignment of the camera with respect to the eye whose motions are to be measured is critical to achieving accurate measurements.

In a preferred embodiment of the present invention that is suitable for use in animal experiments, this desired alignment is achieved by using a suitable head mounting apparatus **14**. Connected to this apparatus **14** is a base **16** which provides the means on which to mount the camera so that it is pointing through the center of the eye.

See FIGS. 2a and 2b for schematics of the experimental set-up of the present invention when the head mounting apparatus and base are configured to accommodate a laboratory animal whose eye rotations are to be measured in response to various applied stimuli. In this situation a gimbal device 18 is used to hold the animal.

In this experimental setup, care must be taken to minimize possible translational and angular alignment errors between the camera 2 and the targeted eye. Translational misalignment occurs when the camera 2 is not pointing through the center of the eye. To achieve the necessary translational alignment, four alignment light sources 20 (e.g., 3 mm diameter white LEDs, NSPW300BS, Nichia Tokushima, Japan) are positioned around the camera 2 in the form of a right-angle cross, with the light sources 20 facing the eye and equidistant from the center of the lens. It should be noted that these alignment light sources could also be placed at differing prescribed distances from the optical axis and they could still be used to assist in providing translational alignment, but with a slightly more complex alignment procedure. Also, it is not absolutely necessary to use four light sources, as two symmetrically placed light sources or a single light source, with its image centered on the camera lens by using a partial mirror, could also be used.

Translational alignment can be achieved by noting that when the camera's optical axis is perfectly orthogonal to a targeted spherical, symmetric, convex reflective surfaces (such as an eye), the four LED reflections seen in the video image are centered on and equidistant from the center pixel of the image. If the camera 2 is tilted with respect to the imaged surface, the LED reflections are no longer equidistant from each other, and the center of the cross they define is no longer aligned with the center pixel of the image. The mounting of the camera to the base is such as to provide the necessary flexibility in its orientation so as to ensure in a pre-test calibration that the reflections seen in the video image are centered on and equidistant from the center of the image. Alternatively, as in the animal experiments, the device holding the animal may provide the means for achieving this desired alignment.

Pure angular misalignment occurs when the camera 2 is pointing through the center of the eye, but the camera coordinate system is not rotationally aligned with the reference coordinate system. In the animal experiments conducted in support of this development effort, the reference coordinate system aligns with the

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animal's head (specifically, with the plane through the animal's horizontal semicircular canals, the midsagittal plane, and the coronal plane orthogonal to these), which in turn is aligned with the head mount apparatus **14**. To ensure correct angular orientation of the cameras with respect to the base (and thus to the animal's head), each camera **2** is mounted on a rotating turret **22** that is adjustable in azimuth and elevation.

Each turret **22** maintains the torsional position of the camera **2** at zero degrees with respect to the head coordinate system. The azimuth and elevation of the camera **2** with respect to this system can be measured with a protractor to an accuracy of 0.25°. These angles are used to convert measured eye rotations into the head coordinate frame of reference.

It can be noted that such angular misalignment errors can be corrected by multiplying each rotation matrix representing instantaneous eye position by the matrix describing rotation from the incorrect frame of reference to the correct frame of reference.

Mixed angular plus translational misalignment occurs when the camera **2** is first brought into perfect alignment and then is rotated so that the camera's optic axis changes direction and no longer points through the center of rotation of the eye. The error due to this combined misalignment can be corrected post-hoc if the translational and angular deviation from the ideal camera position are known.

FIGS. 3a and 3b present schematic side and top views of an experimental set-up of the present invention that has been configured to allow for eye position measurements in humans. Again, the basic parts of the present invention are seen to be a digital video camera **2** with a modified lens **4** and optical filter **10** that are used to track an array of three 1 mm x 1 mm markers **6** positioned on the cornea of the patient's eye and illuminated with a suitable light source **12**.

In this embodiment, a suitable eye-mask type configuration **24**, with its head mounting straps **26**, is used to mount and orient the camera **2** and light source **12** in front of the eye whose motions are to be measured. Alignment lights **20** (e.g., LEDs which may be visible, infrared or ultraviolet light) are symmetrically positioned about the camera optical axis and are here shown to be mounted on the camera's housing, but may also be mounted in other positions sufficient to illuminate the eye (e.g., on an inner surface of the mask or external to the mask).

Shown in FIG. 4 is another embodiment suitable for measuring human eye movements in those instances in which it is desired to not obstruct the patient's

view. In this embodiment, a mirror **28** which is partially transparent is mounted and aligned in front of the patient's eyes in such a manner that it allows the camera to be mounted to the side of the patient's eyes.

It should be recognized that there exist many alternative ways to mount a camera attached to a suitable head device or mask so that eye movements can be tracked and recorded. For example, a camera could be mounted down nearer a patient's cheeks so that the camera looks up into the eyes and doesn't obstruct one's straight ahead vision. All such camera orientations and consequent modifications of the mask or head device are considered to come within the realm of the current invention.

It can be noted that the development of a high frame rate version of the present invention has been facilitated by recent advances in complementary metal oxide semiconductor (CMOS) imaging technology, digital video cameras and computer interfaces.

CMOS imaging technology has, for many years, been considered to be inferior to charge-coupled devices (CCD). However, CMOS technology does have one major advantage over CCDs in that it can be manufactured using the same methods and equipment used for normal silicon chip production. For this reason CMOS technology is cheaper and evolves at a much faster rate than CCD sensors, which can only be made by a small number of large manufacturers. The quality of video images produced by CMOS sensors is now as good as, or in some cases better than, those from CCDs.

CMOS technology also allows for the integration of video processing on or near the sensor itself. This processing provides the opportunity to simplify the eye movement analysis task by shifting some of the processing burden on to the camera hardware and off the computer CPU. Tasks such as the automatic adjustment of brightness and contrast, the dynamic modification of look-up tables, conversion to bitmap, and variable region of interest can all be done in the camera.

Another important development in camera technology is the increasing use of digital imaging systems. Digital video cameras digitize on or close to CMOS or CCD and avoid the problems of noise and interference inherent to systems that pass analogue video signals down long leads. Digital video cameras are proving to be smaller, lighter and cheaper, and have lower power consumption than an equivalent combination of analogue camera and acquisition card for digital-to-analogue conversion.

1   Digital cameras can interface directly with a number of high-speed bus

2   types, including Firewire (IEEE1394) and USB 2.0 that are standard, buit-in

3   features of recent PC and Macintosh computers. Because laptop computers also

4   incorporate these high-speed bus technologies, eye movement recording systems

5   can now become truly mobile.

6   A laptop, notebook or sub-notebook computer can analyze or store video

7   data from a camera without any external source of power. This means that video

8   eye movement analysis systems can now be used at a patient's bedside in the

9   clinic or carried by a freely moving subject untethered to an experimental

10   apparatus.

11   The biggest advantage of digital camera systems for eye movement

12   analysis may be that they avoid the limits imposed by analogue video standards.

13   It is possible to exceed the 25-30 Hz frame rates of domestic video equipment by:

14   (a) de-interlacing frames into two fields, (b) using special double-speed cameras

15   with more than one analogue video output, (c) using multiple digital to analogue

16   converters, and (d) modifying camera electronics. These methods are

17   complicated, processor intensive, and often very expensive because there is a

18   small market for this esoteric equipment. Digital cameras can be programmed to

19   transfer images of arbitrary size, adjustable pixel depth, variable region of interest,

20   and have frame rates limited only by the bandwidth of their digital hardware.

21   Since the Firewire bus permits a throughput of 400 Mbps and a UBS 2 a

22   throughput of 480 Mbps, a high fame rate is possible, especially by transferring to

23   the computer only the region of the image that is useful for eye movement

24   analysis.

25   These advancements have been especially important in the development of

26   portable eye movement measurement systems suitable for use with humans. This

27   portability has been made possible by the development of the above described,

28   new digital (IEEE 1394, "Firewire" or USB 2.0) camera technology. These

29   cameras can be   directly connected to signal and power via the Firewire port on

30   laptop computers so as to yield a stand-alone, wireless and battery-powered eye

31   movement analysis system that is capable of processing eye movements at 30 Hz

32   online and in real time. The use of notebook computers and even the new sub-

33   miniature notebook computers (e.g., Sony PictureBook which weights less than 1

34   kg) hold the promise of adding even more portability to such systems.

A camera 2 suitable for use in the system of the present invention was found to be an IEEE 1394 Firewire webcam (PYRO1394 WebCam, ADS Technologies, USA) retrofitted with ¼" format 16.0 mm focal length, f/2.0 C-mount board lens (BL160, Allthings Inc., Australia). This camera was used to acquire 640 x 480 pixel B&W (8-bit) images at 30 Hz.

For use with such a camera and a 16 mm lens 4, a 5 mm plastic spacer is placed between the lens housing and the printed circuit board of the webcam so as to allow the camera to be focused on a point 50 mm away.

National Instruments LabVIEW 7.0, NI-IMAQ Vision 7.0.1 and NI-IMAQ for IEEE 1394 Cameras 1.5 standard modules were used to control camera settings such as contrast and brightness and to correct for lens distortion and perspective.

Standard NI-IMAQ modules were used to change the image threshold so that only the markers 6 were visible on a black background and to determine the center of each marker using a center of mass algorithm.

Camera magnification is set so that the medial and lateral canthi are at the edges of the video image. Pixel size was calibrated using a known distance between markers 6 and verified by using a micrometer.

Appropriate light sources 12 for this system include a diffuse ultraviolet (UV-A) light source (360 nm peak, 9 Watt, FPX7BLB, Ushio Inc., Japan) or 80 nm UV-A light-emitting diodes (LEDs) (SSL-LX5093SUVC, Lumex Inc.).

Depending on the spectral sensitivity of the specific camera used, a UV cut filter 10 (SKYLIGHT 1B Hoya, Japan) or a yellow pass filter (K2 yellow filter Hoya, Japan) can be used to improve contrast. No filter was necessary when the webcams described above were used because their color CCD is already less sensitive to UV than most monochrome image sensors.

The maximum allowable exposure of UV-A (320-400 nm) that will not harm the eye (cornea and lens) for human use is 1 J/cm^2. The "black light" or UV-A lamp (sometimes called a "Wood's Lamp") that was used in this invention's development work is not considered hazardous because the UV-A radiance at the lamp surface is only about 3 mW/cm^2. At 30 cm distance the UV-A radiance at the eye surface is about 50 $\mu W/cm^2$ and would require > five hours exposure to reach 1 J/cm^2. The UV LED light source generates about 3 mW, the beam angle was 30° so at 20 cm the UV-A radiance at the eye surface was about 33 $\mu W/cm^2$ and would require > eight hours to reach 1 J/cm^2.

1   A number of types of markers **6** are suitable for use with various preferred

2   embodiments of the present invention. For example, one could use the previously

3   described array of three 1mm x 1 mm markers **6** on a piece of plastic film **8** that is

4   affixed to the cornea of the eye.   Alternatively, one could, in certain

5   circumstances, forego the use of an affixed marker array and instead tattoo or etch

6   markers **6** onto the eye.

7   The markers **6** of the present invention are chosen so as to allow for the

8   use of optical methods that increase marker signal-to-noise ratios above that of

9   corneal reflections.

10   One such technique involves using a fluorescent marker array illuminated

11   by UV-A light source. This array can be fabricated using plastic film **8** laminated

12   on paper saturated with fluorescent yellow ink. The film is opaque except for

13   three transparent 1 mm x 1 mm windows separated by 1 mm and arranged in a 45°

14   right triangle [:.]. The distance between the windows of the plastic ink backing

15   tape is fixed at 1 mm. For experiments requiring intact vision, the marker array is

16   placed away from the pupil, or on an annular contact lens **30** and is illuminated

17   with a UV-A light source. See FIG. 5.

18   Alternatively, a marker array using anti-Stokes (or 'up-converter')

19   fluorescent pigments may be used with infrared illumination. In contrast to most

20   fluorescent pigments, which can only emit wavelengths longer than those they

21   absorb, anti-Stokes pigments emit visible light under infrared illumination

22   (inorganic oxisulphide emits at 550 nm). As with the UV-fluorescent markers

23   described above, the spectral shift between the infrared illumination source and

24   the marker emissions still allows the use of optical filters to remove corneal

25   reflection artifacts. This approach has the additional benefit that the marker array

26   need not be positioned over the pupil for experiments that require absence of

27   visual input, because the infrared light sources are not visible.

28   Another marker possibility, especially suited for use with humans, is the

29   construction of a silicone scleral "contact lens" with fluorescent markers **6**

30   embedded into such lens.

31   The data acquisition and analysis task of the present invention was

32   accomplished with the use of the Pentium IV 2.4 GHz 1 GB RAM computer

33   processor **32** of a desktop personal computer running Windows 2000. This

34   hardware and the appropriate software allowed binocular, three-dimensional eye

35   positions to be computed and displayed in real-time using an intuitive graphical

1   user interface **34**. The LabVIEW G programming language (National Instruments,

2   Austin, TX) can be used to simplify the invention's software development.

3   The three-dimensional eye rotation necessary to move a marker array from

4   a reference position to a final position is calculated in the present invention by

5   using a mathematical method that is simpler and more efficient than others

6   previously used.

7   Assuming the eye is a sphere that rotates about its center (or more

8   precisely, that as the marker array moves with the eye, it travels along a spherical

9   surface of radius approximately equal to that defined by the eye's globe-shaped

10   outer surface), assuming the eye is centered on the camera's optical axis, and

11   defining the center of the eye as the origin of a coordinate system (**i, j, k**), one can

12   calculate the position in space of each marker. See FIG. 1.

13   The marker array can be positioned anywhere on the eye as long as it

14   remains visible during eye rotations. The **i, j** and **k** axes measure translation of

15   each marker in space, with **j** and **k** equaling the horizontal and vertical positions

16   of each marker (measured in pixels) from the center of the video image, and **i**

17   being the distance from the globe center to the marker along the optic axis of the

18   camera. The **i** coordinate is calculated from **j** and **k** and the known radius of the

19   eye as follows:

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21   $$i = \sqrt{\left((eye\_radius\_in\_pixels)^2 - \left(j^2 + k^2\right)\right)}$$

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23   The rotation matrix $\mathcal{R}$ uniquely describing the eye rotation required to

24   move the three markers from one position to another is:

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27   $$\mathcal{R} = \begin{bmatrix} i_0 & i_1 & i_2 \\ j_0 & j_1 & j_2 \\ k_0 & k_1 & k_2 \end{bmatrix}_{current} * \begin{bmatrix} i_0 & i_1 & i_2 \\ j_0 & j_1 & j_2 \\ k_0 & k_1 & k_2 \end{bmatrix}_{ref}^{-1}$$

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29   The subscript *ref* refers to the marker position before a rotation and defines

30   the reference or zero rotational position of the eye. The subscript *current* refers to

31   the marker positions in 3-D space after a rotation. Euler angles, rotation vectors

1   and quaternions are calculated directly from the rotation matrix; see previously

2   referenced Migliaccio and Todd, 1999.

3   The steps in the above eye position calculation aspect of the present

4   invention are further illustrated in FIGS. 6a-6b.   The images shown in these

5   figures were obtained from a digital camera as described herein and connected to

6   a personal computer via a IEEE1394 Firewire bus 36.

7   Using 640x 480 pixel cameras and magnification optimized so that the

8   marker array range of motion filled the camera image frame, the absolute

9   resolution of an experimental system that was assembled to demonstrate the

10 feasibility of the present invention (assuming minimum detectable image shift of

11 one pixel) was found to be <0.2°.

12   As previously mentioned, the accuracy of the above algorithm depends on

13 alignment of the camera center with the center of the eye, which was ensured

14 using the techniques described above. If unusual circumstances dictate that the

15 camera cannot be precisely aligned with eye (e.g., in an experimental apparatus

16 with limited space for camera placement), translational and angular misalignment

17 can be corrected post hoc if the misalignment is known.

18   The correction must be in the following sequence. First, translational

19 misalignment can be corrected by redefining the image center so that rather than

20 using the default (center pixel of the camera image), the image pixel that aligns

21 with the center of rotation of the eye is defined as the origin. Second, angular

22 misalignment can be corrected by multiplying each eye rotation matrix by the

23 inverse rotation matrix describing camera rotational position in the reference

24 coordinate frame (whether head or superstructure/test-apparatus coordinates).

25   Tracking of one or more markers may be transiently lost during a blink,

26 burst of saccades or extreme eye deviation that moves the markers behind the

27 retracted eyelid or into a poorly illuminated region. Upon subsequent

28 reacquisition of the marker image, potential uncertainty exists regarding which

29 marker is which.

30   One approach to resolving this ambiguity would be to separately track

31 each marker using different colors, shapes, sizes or relative positioning in the

32 marker array. Alternatively, if the eye is assumed to stay within the ~45°

33 oculomotor range, then only one of six possible permutations gives the correct

34 pairing of all three markers from one image to the next, even if intervening images

35 have been lost.

1   In experiments conducted to prove the feasibility of the present invention,

2   the correct pairing was determined by calculating the summed square of marker

3   travel distances for each permutation and accepting the permutation that resulted

4   in the smallest value. The correct permutation was always selected, regardless of

5   the cause or duration of transient marker image loss.

6   Because binocular video analysis is computationally intensive, the code

7   written for the data analysis was optimized using NI-IEEE 1394 software

8   interrupts, freeing the CPU for other processing until a new video image was

9   acquired. Camera output was time-shifted to account for the delay between image

10   acquisition at the image sensor and arrival of the new image in PC memory. This

11   delay was found to be 33.2 ± 0.1 ms by measuring the time delay between actual

12   and VOG-derived motion of a digitally-controlled motor turning a simulated eye

13   tracked by the VOG system continuously for five minutes.

14   Although the foregoing disclosure relates to preferred embodiments of the

15   invention, it is understood that these details have been given for the purposes of

16   clarification only. Various changes and modifications of the invention will be

17   apparent, to one having ordinary skill in the art, without departing from the spirit

18   and scope of the invention.

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